Modeling Debris-Flow Sediment Transport in Grand Canyon

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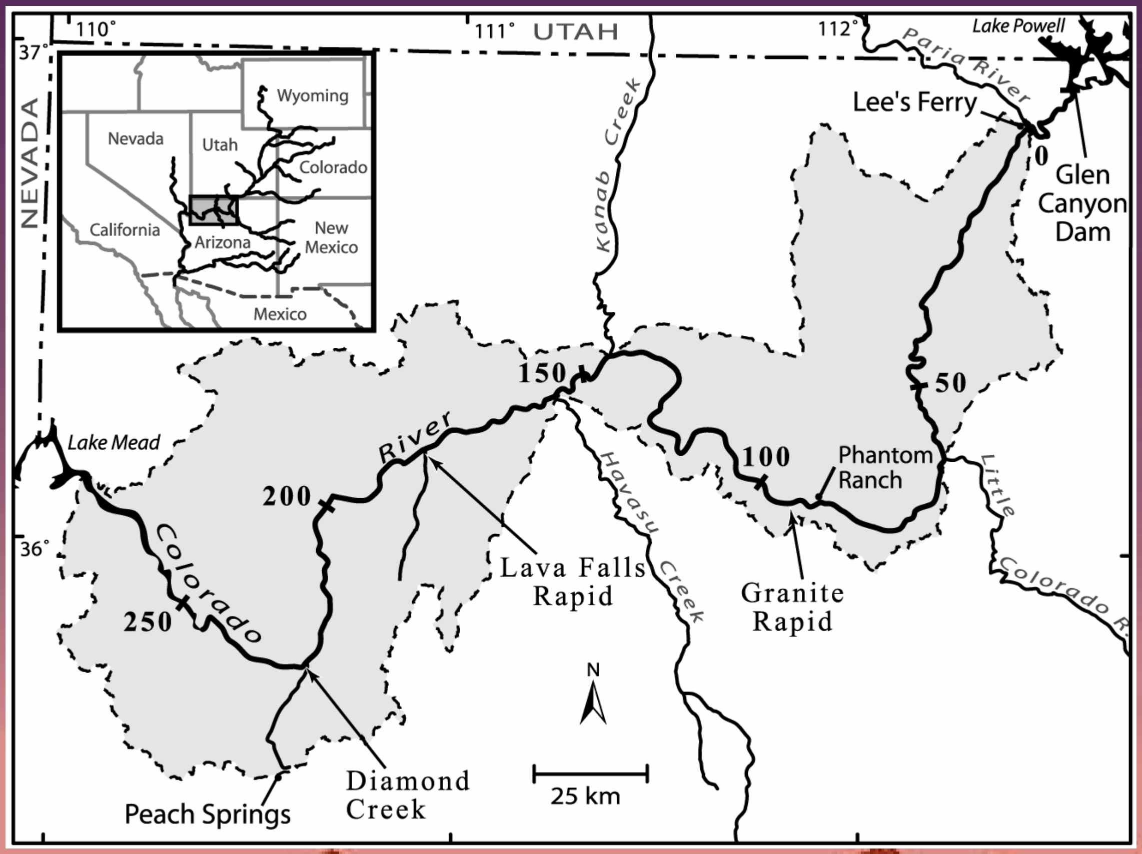
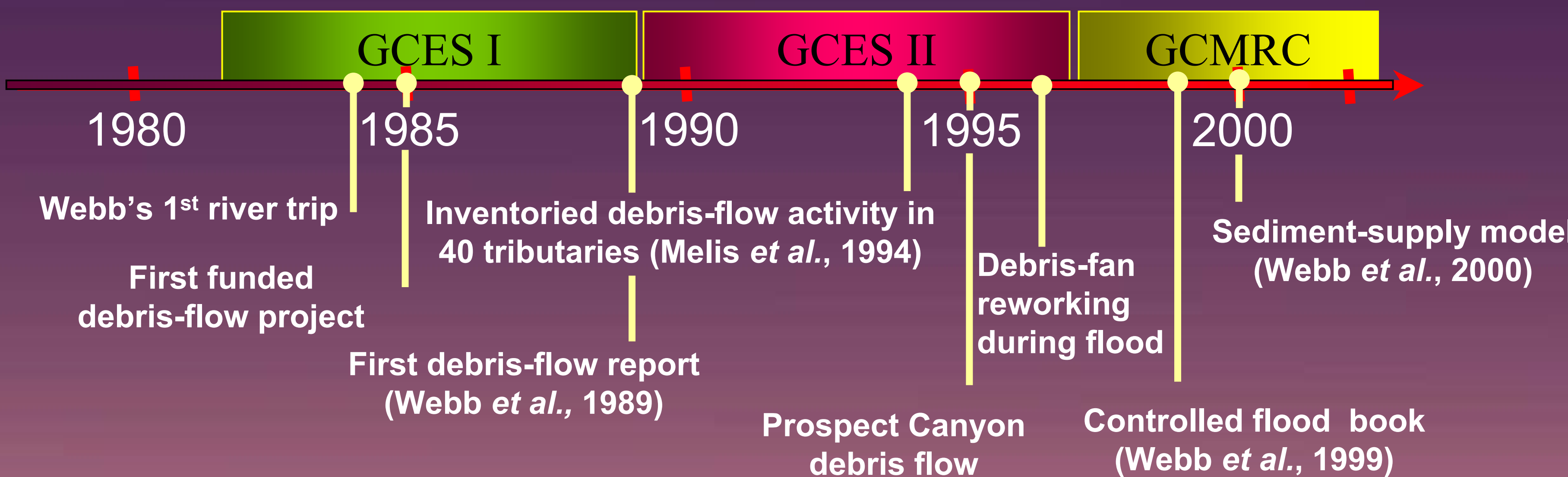


Purpose of Research Project

Monitor and study the contribution of coarse-grained sediment into Colorado River within Grand Canyon from all tributaries and evaluate impact on river.

History of Research Project



COLLABORATORS:
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John Elliott (USGS)

M.S. STUDENTS:
Peter Griffiths (1990-96)
Dan Hartley (1998-00)
Tillie Klearman (2000-2002)
Andy Persio (2002-present)

Ph.D. STUDENTS:
Ted Melis (1990-97)
Chris Magirl (2000-present)

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What is a Debris Flow?

- Debris flows are slurries of poorly sorted sediment and water
- Particles range from clay to boulders 3-20 feet in b-axis diameter
- Typical moisture contents reconstituted from Grand Canyon debris flows range from 10-25% (n=49)
- Three types of flood hydrographs with a debris-flow component occur in Grand Canyon

Ref: Webb et al., 1989, USGS Prof. Paper 1492

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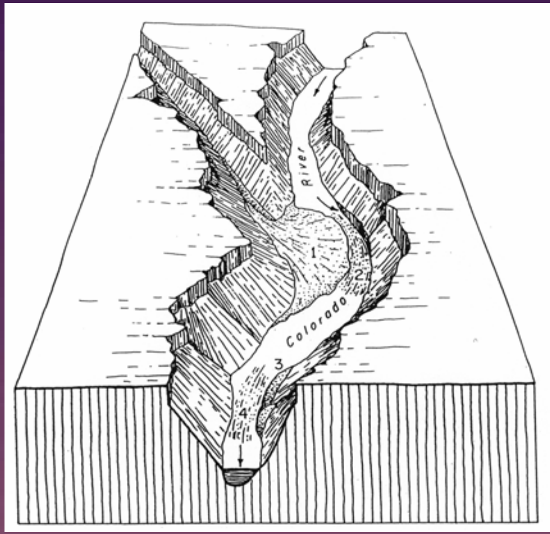
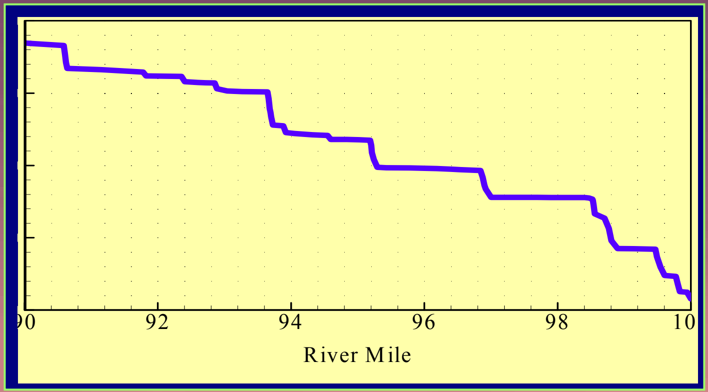
SIGNIFICANCE OF DEBRIS FLOWS

- Debris flows threaten humans and structures
- Debris flows create rapids and eddies that are efficient sand traps and create beaches
- Debris flows add boulders and cobbles to the river that form substrate for aquatic plants
- The occurrence of debris flows influences the types of native fishes present in the river





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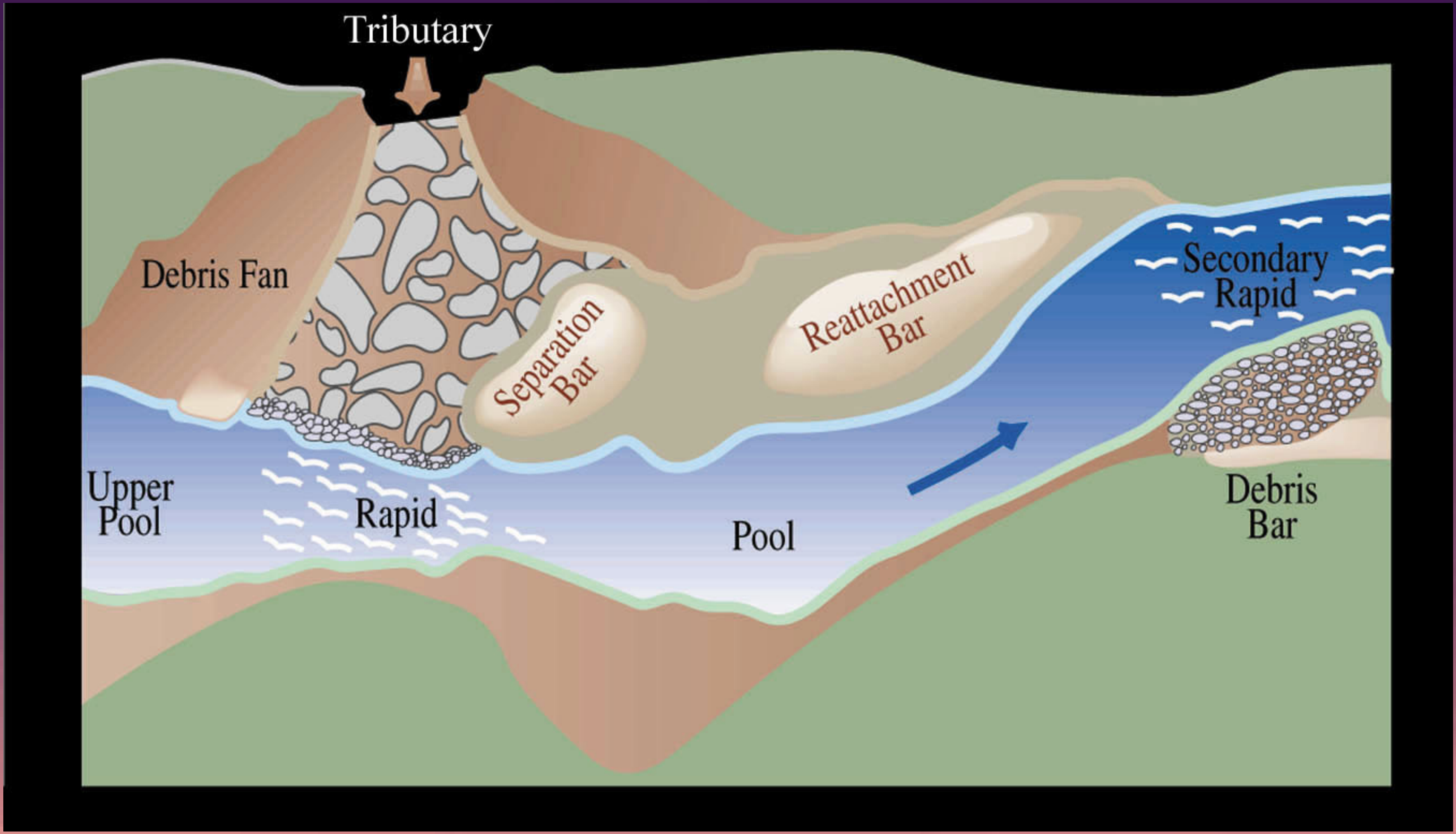
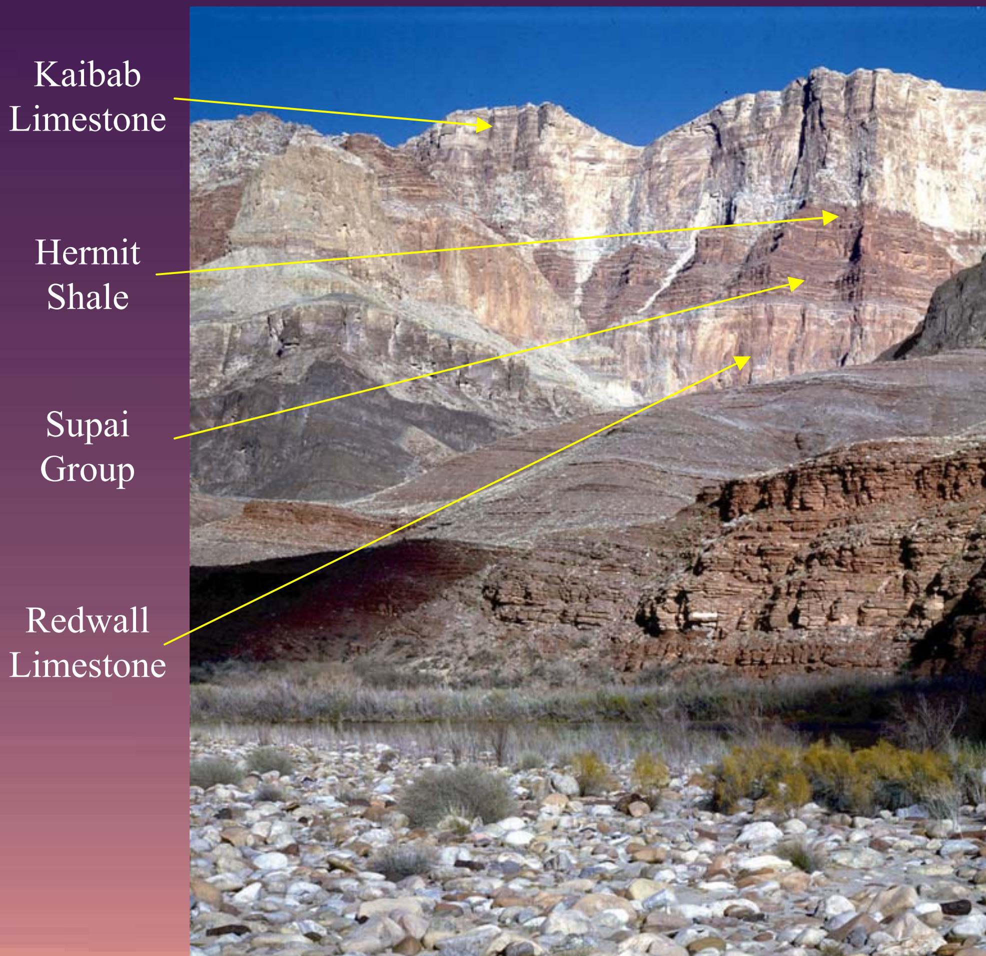
Significance of Debris Flows



Ref: Webb et al., 1989, USGS Prof. Paper 1492

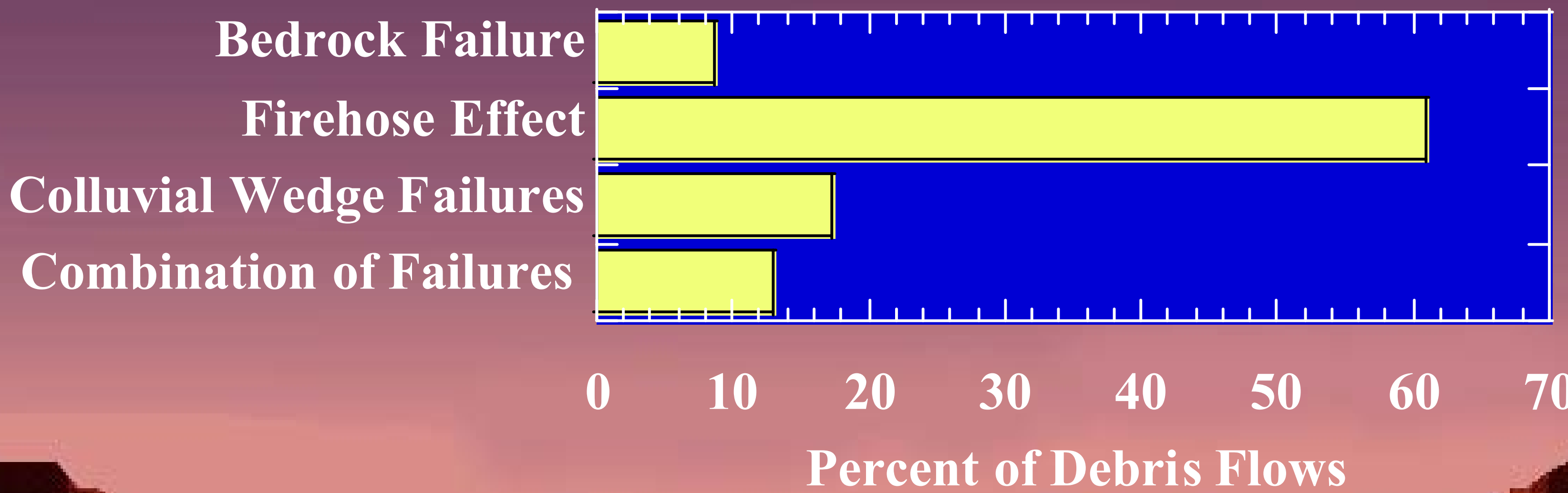
Debris Flows and Bedrock Geology



- The weakest rocks – shales – contribute clay to debris flow matrix
- Hermit Shale and other shales are important clay sources to colluvium and through direct failures
- Boulders from hard layers form rapids

Initiation of Debris Flows

- Single-layer clays (*e.g.*, kaolinite) produce more debris flows than multilayer clays (*e.g.*, smectites)
- Four initiation mechanisms
- Rainfall intensities >1 in./hr
- Intense storms, not wet seasons



Ref: Webb et al., 2003

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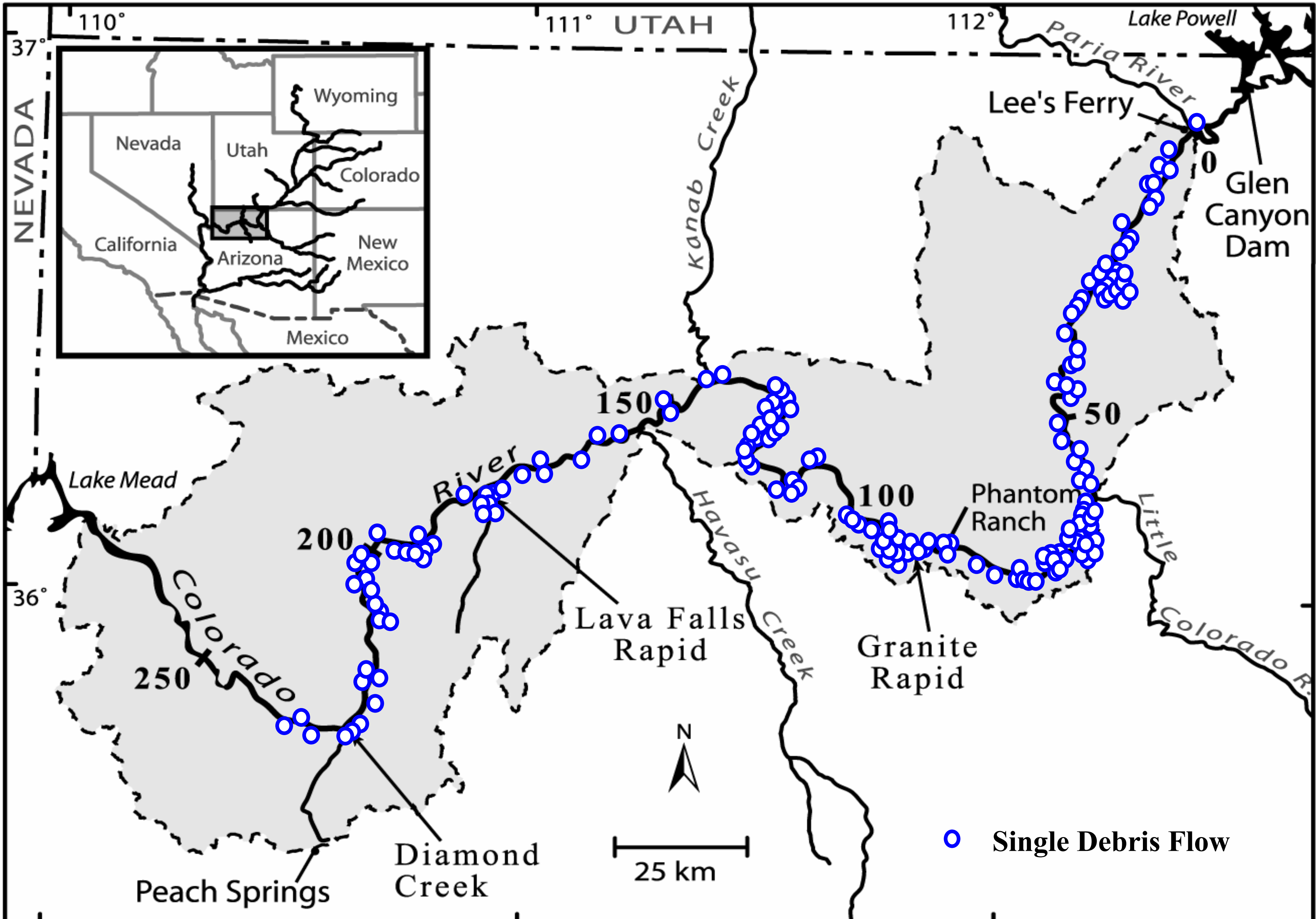
Distribution of Historical Debris Flows (1872-2002)



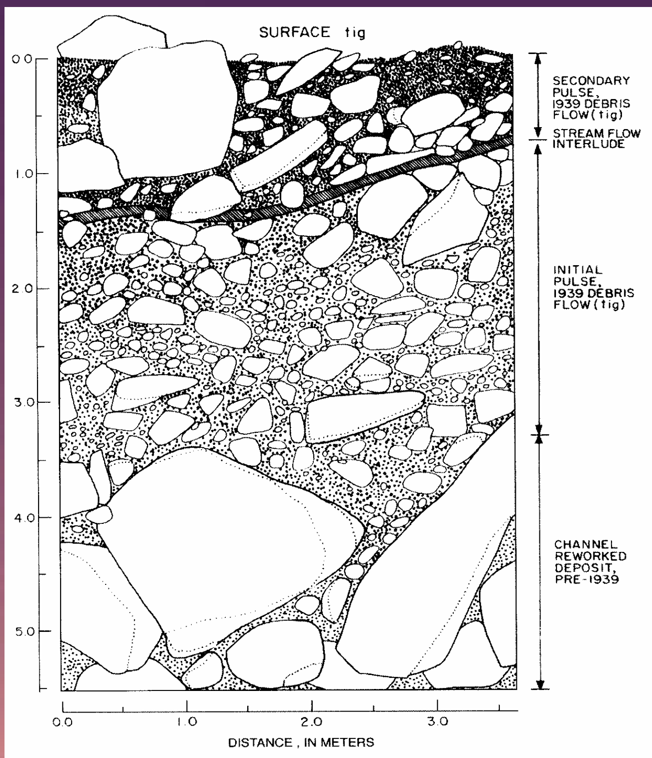
Frequency of Debris Flows

How do you study rare events when few have been watching or measuring?

1. Stratigraphy (^{14}C, ^{3}He, other dating methods)
2. Historical diaries (1869-1964)
3. Direct observation (1984-2002)
4. LIDAR remote sensing (2000)
5. Repeat photography (1871-2002)

Stratigraphic Analyses of Debris Flows

- It is very difficult to recognize individual debris flows in section
- Stratigraphy is self-censoring and does not record all events



- Oldest known flow, 8,500±200 years ($^{3}He_{c}$), in Whitmore Canyon (mile 189). This debris flow did not reach the river.
- Largest known debris flow to reach river is at Lava Falls (mile 179.3): 3,000±500 years ($^{3}He_{c}$)
- Many debris flows dated from 300 – 5,400 years using ^{14}C

Ref: Hereford et al., 1996, GSA Bull.; Hereford et al., 1998, Quat. Res.; Webb et al., 1999, USGS Prof Paper 1591

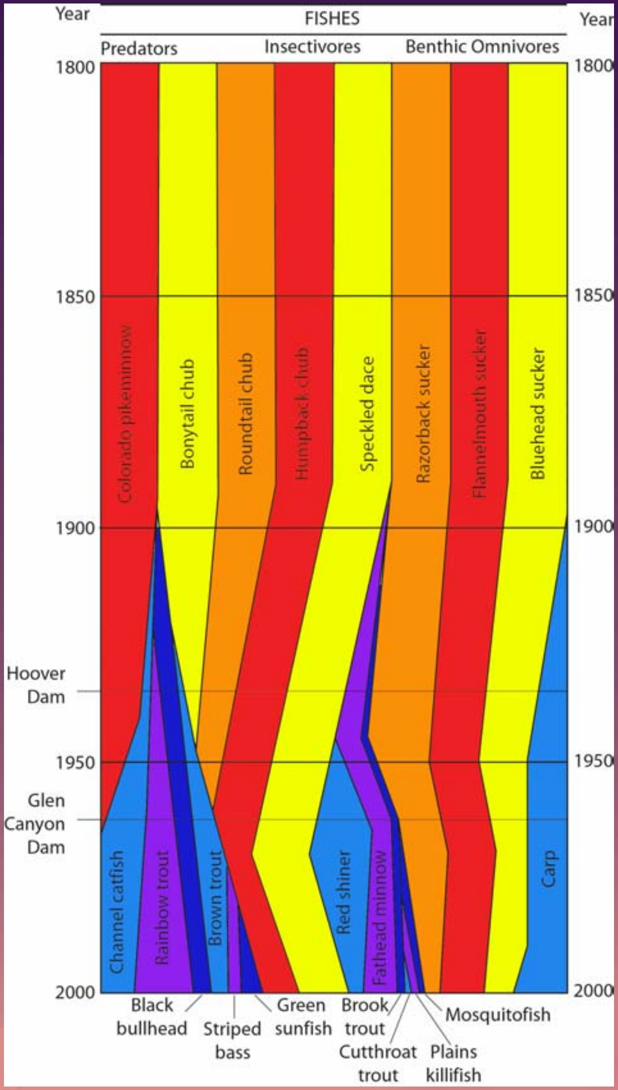
Historical Observations: The Old Timers

- Examined 67 diaries (1872-1964)
- Sponsored “Old Timers” float trip in 1994

Bottom Line:

- Human observations are unreliable when they are not trained to recognize complex phenomena like debris flows
- Some people saw important events but in general no one reliably recognized changes in debris fans
- Other changes, such as increases in riparian vegetation and beach erosion, were accurately identified

Historical Observations: Fishes



- The earliest river trips caught Colorado salmon (pikeminnow) and humpback suckers (chub).
- Dynamiting for fishing was common in Glen Canyon, at Lee's Ferry, and near Whitmore.
- At first, dynamite yielded pikeminnow. Later, dynamite yielded only catfish.
- Trout, first stocked in tributaries in the 1920s, were caught in the river before Glen Canyon Dam was completed.

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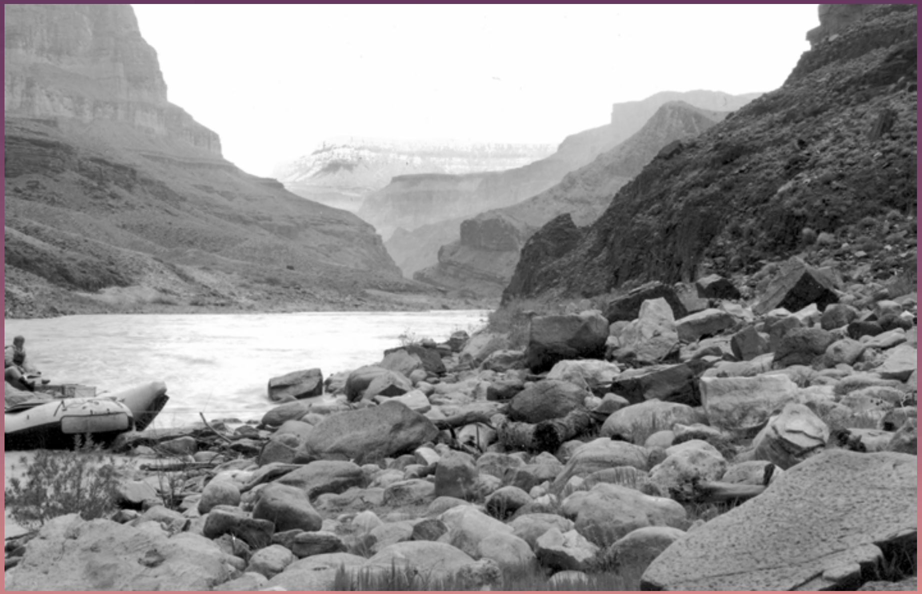
Historical Observations: The Old Timers

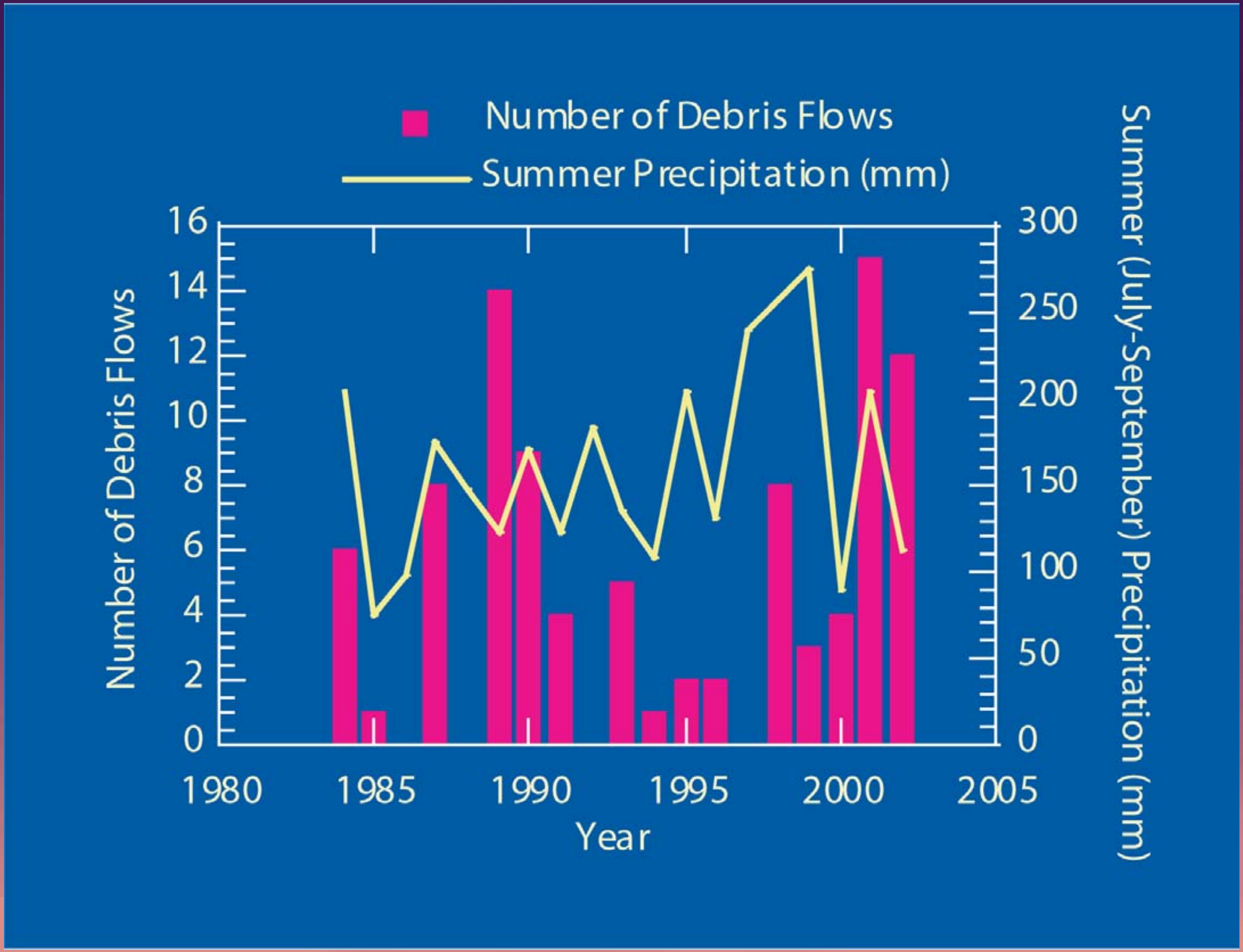
- Many sandbars used on pre-dam river trips are no longer present (e.g., downstream from Tapeats Creek)
- The largest change they saw in Grand Canyon was erosion of sand bars downstream from Nankoweap Creek



Observed Debris Flows, 1984-2002

- From 1984-2002, a total of 95 debris flows were observed in Grand Canyon (5.0/yr)
- 9 increased the severity of existing rapids
- 7 changed existing riffles into rapids
- 3 created new riffles

Observed Debris Flows, 1984-2002



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Geomorphic Change Detection in Grand Canyon: Comparison of 2000 LIDAR and 1923 Survey Data

1923 Birdseye Expedition

2000 LIDAR Overflight

Grand Canyon water-surface profile has been measured only twice:

1. By Colonel Claude Birdseye on the 1923 USGS expedition.
2. Through analyzing data from the 2000 LIDAR overflights.

Ref: Magirl et al., in preparation

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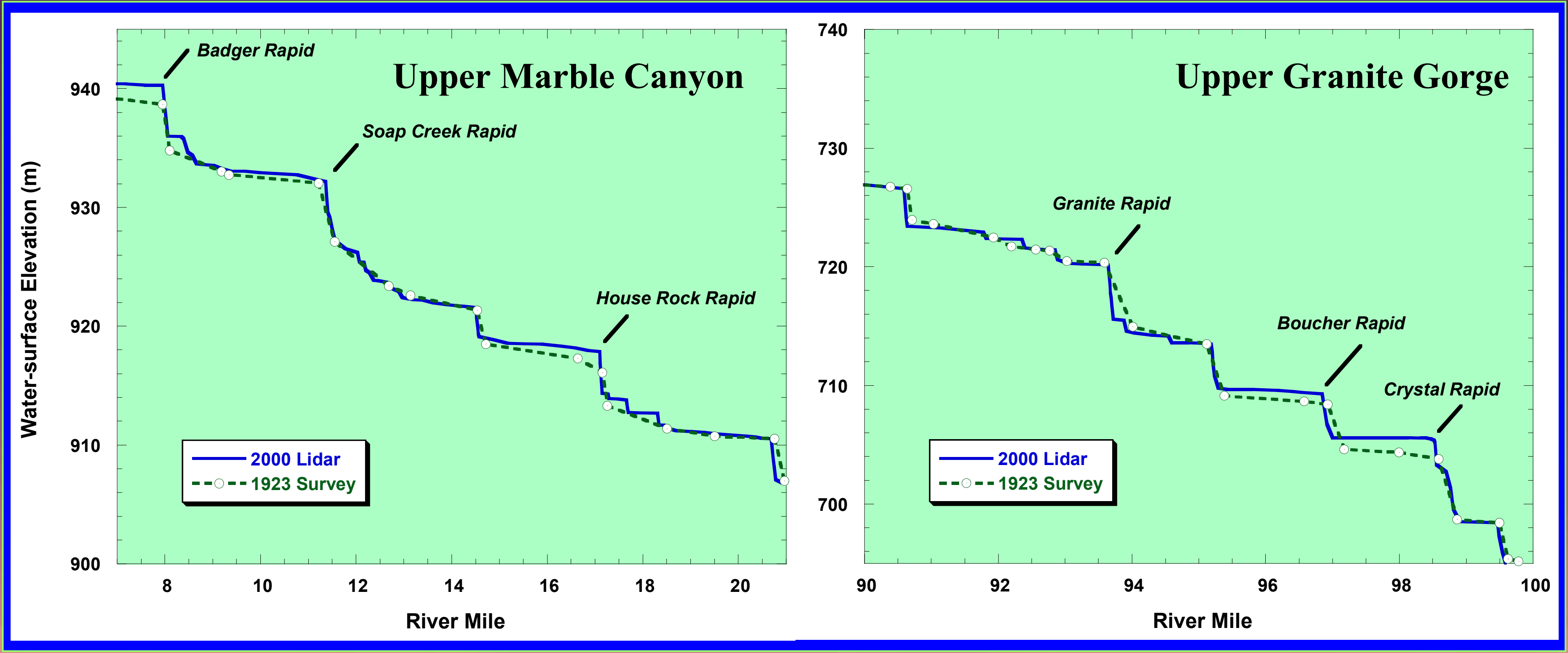
Direct Comparison of Water-Surface Profiles Over 77 Years

- Quantify change in water-surface elevation from 1923 to 2000
- Detect the presence of previously unknown debris flows
- Calculate new set of geomorphic statistics for Grand Canyon



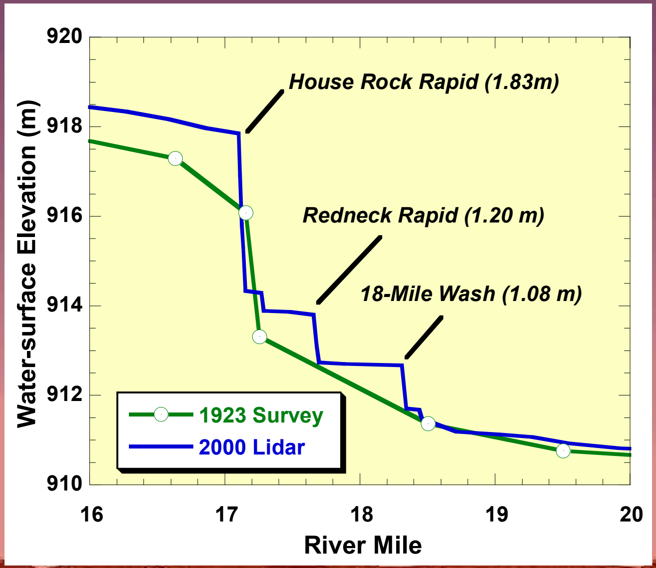
Ref: Magirl et al., 2002, GSA Abstracts

Largest Rise at Head of a Rapid

House Rock Rapid, mile 16.8

1923

1991



Net Rise: 6.0 feet

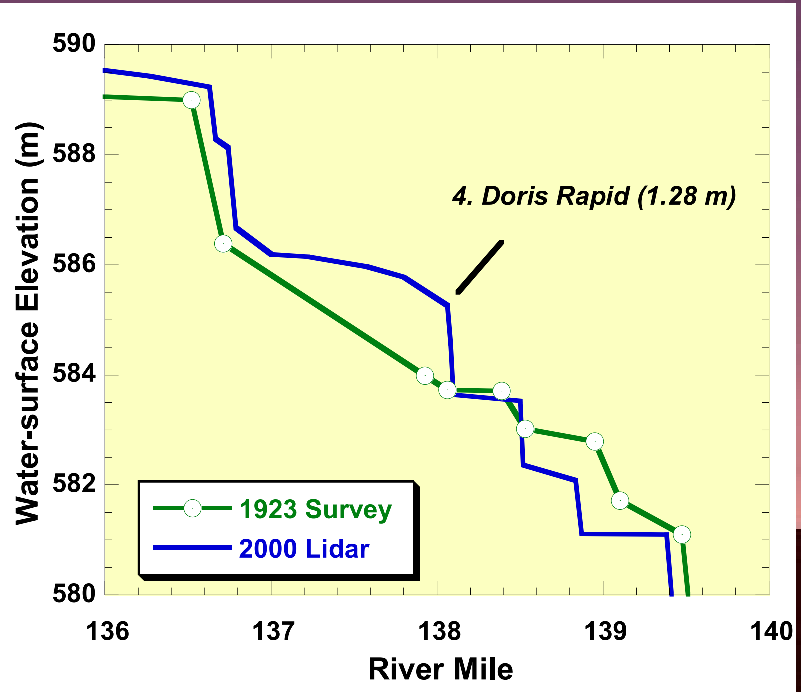
Detection of Previously Unknown Debris Flows

The riddle of Doris Rapid (mile 137.7):

- 1890: Stanton reports a 8-10 foot drop
- 1923: Birdseye measures a 1 foot drop
- 1940: Doris Nevills swims an enlarged rapid
- 2000: LIDAR measures a 5 foot drop

Possible Explanation:

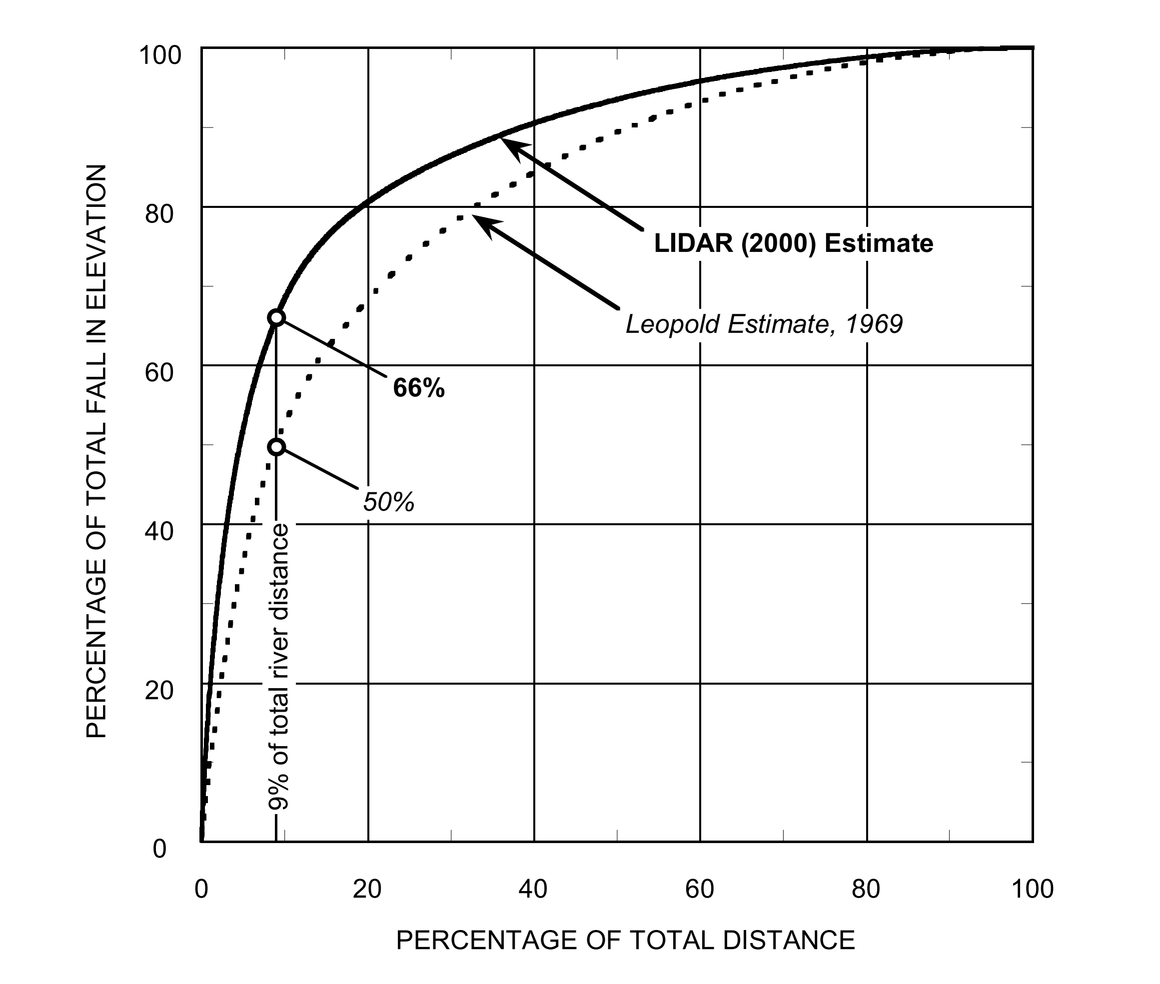
1. Debris flow occurs between 1884-1890
2. The 220,000 ft^3/s flood in 1921 reworks the first deposit
3. A second debris flow occurs between 1923-1940



Geomorphology of the River

Luna Leopold (1969) states …*50% of total decrease in elevation takes place in only 9% of the total river distance*…[based on Birdseye profile]

New estimate, based on 2000 LIDAR profile: 66% of drop in 9% of distance



Ref: Magirl et al., in preparation

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Repeat Photography and Debris Flows

- Matched 1,365 photos showing debris-flow evidence
- Earliest photo—1871; Most useful group—1890 (Stanton)
- 113 debris flows at 160 tributaries (1890-1983)
- Extrapolating…4.6 debris flows per year (1890-1983)

Ref: Webb 1996; Webb et al., 1999, USGS Prof Paper 1591

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Crystal Rapid

1966 Debris Flow Effects

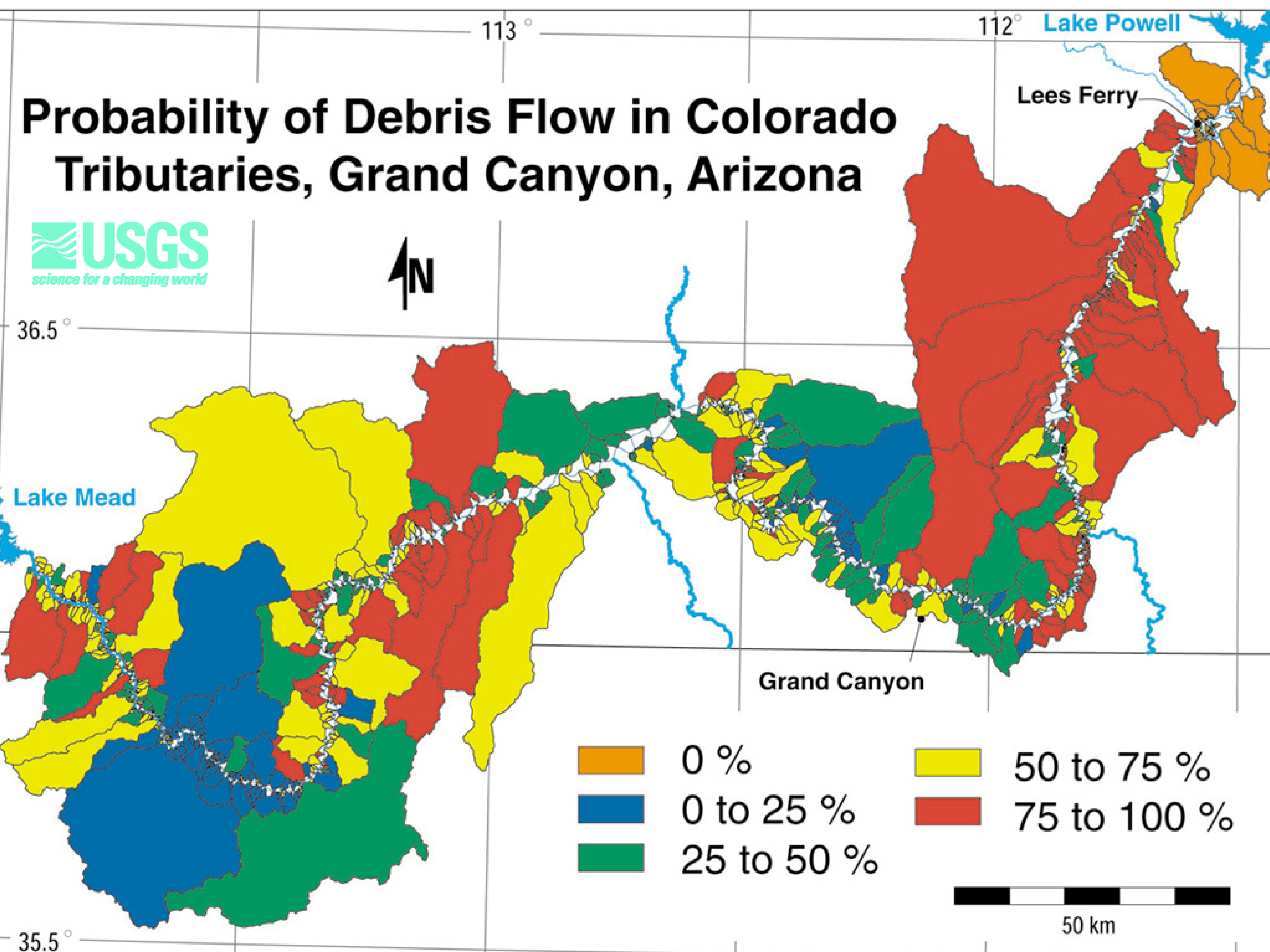
1890

1990

Ref: Webb 1996

Logistic Regression

- Repeat photography captures 160 tributary mouths, 1890-1990
- We record 94 tributaries that had at least one debris flow (~60% of tributaries)
- We analyze debris-flow occurrence as “yes/no” categorical data with 22 geologic and morphologic variables
- We calculate debris-flow probabilities with 6 significant variables



Probability of Debris Flow in Colorado Tributaries, Grand Canyon, Arizona
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N
113°
112°
36.5°
35.5°
Lake Powell
Lees Ferry
Lake Mead
Grand Canyon
0 %
0 to 25 %
25 to 50 %
50 to 75 %
75 to 100 %
50 km

Debris Flows and Native Fishes

- Areas where humpback chub are most common are areas with highest debris-flow frequency.
- In 1993, radio-tagged humpback chub were attracted to the newly aggraded debris fan at Tanner Rapid.
- Debris flows occur in Little Colorado River canyon and could block upstream migration for the chub if a large event occurs in future.

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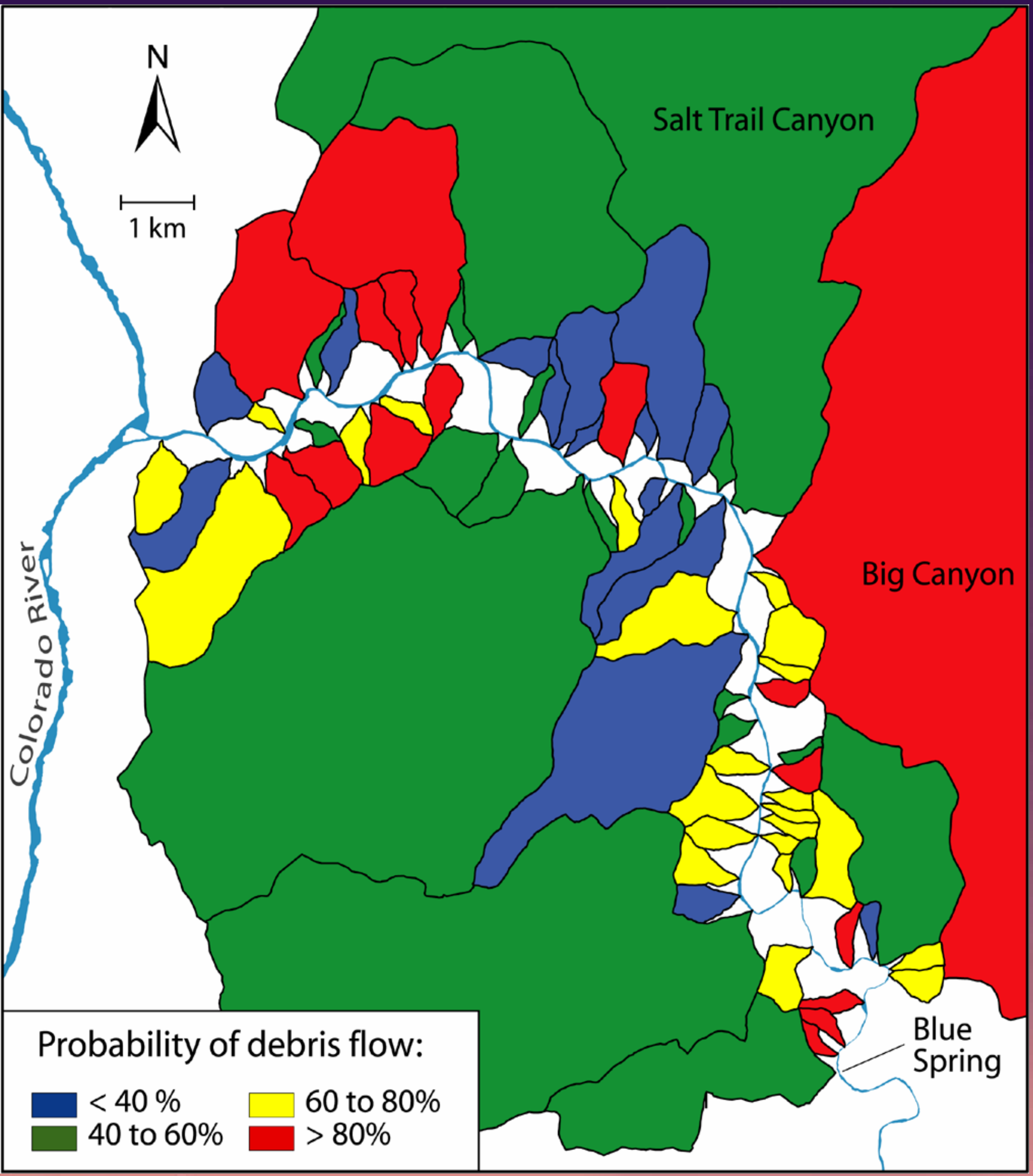
Debris Flow and the Little Colorado River



- 74 tributaries occur in reach up to Blue Spring. 53% have a debris-flow probability > 60%.
- LCR tributaries are comparable to those along the Colorado and should generate similar quantities of coarse sediment.
- LCR channel is narrower than that of the Colorado and more susceptible to the effects of debris flows.
- Debris flows could block channel in reach within 1-2 miles of the Confluence.

MODELING DEBRIS-FLOW SEDIMENT YIELD

Based on substantial data on debris flows, we developed predictive models to predict possible changes in Grand Canyon rapids (hazard index).

1. Debris-flow frequency model (logistic regression)
2. Sediment-yield model for Grand Canyon tributaries
3. Particle-size distributions for debris flows
4. Debris-fan reworking

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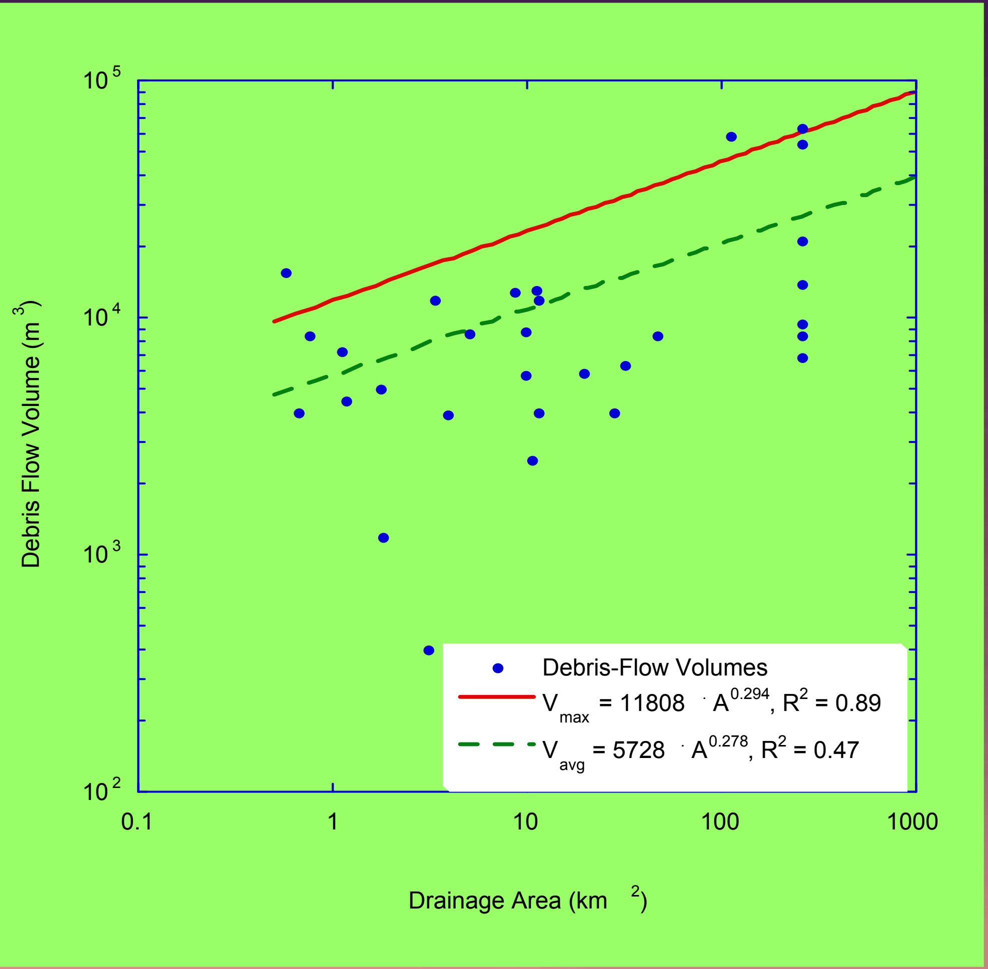
Debris-Flow Sediment-Yield Model for Grand Canyon Tributaries



$$Q_{sdf} = 0.17 \cdot F[\pi(x)] \cdot a \cdot A^b$$

where

Q_{sdf}	= sediment yield per decade
$F[\pi(x)]$	= the DF frequency factor
a, b	= empirical coefficients
0.17	is a conversion factor.

Ref: Webb et al., 2000, USGS WRIR 00-4015

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Modeling Coarse Sediment Inputs

- Debris-flow sediments, on average, are 14% boulders, 65% gravel and cobbles, and 18% sand.
- Model predicts sediment inputs into the river based on long-term averages.
- This model could be used to predict (with a river-reworking component) where gravel would accumulate in Grand Canyon

Ref: Melis, 1997, Ph.D; Webb et al., 2000, USGS WRIR 00-4015

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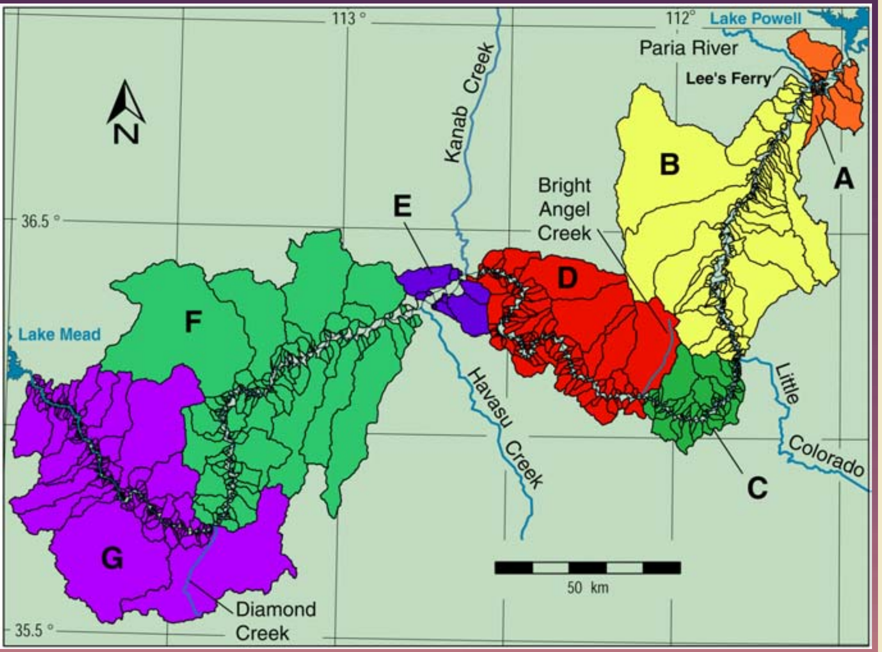
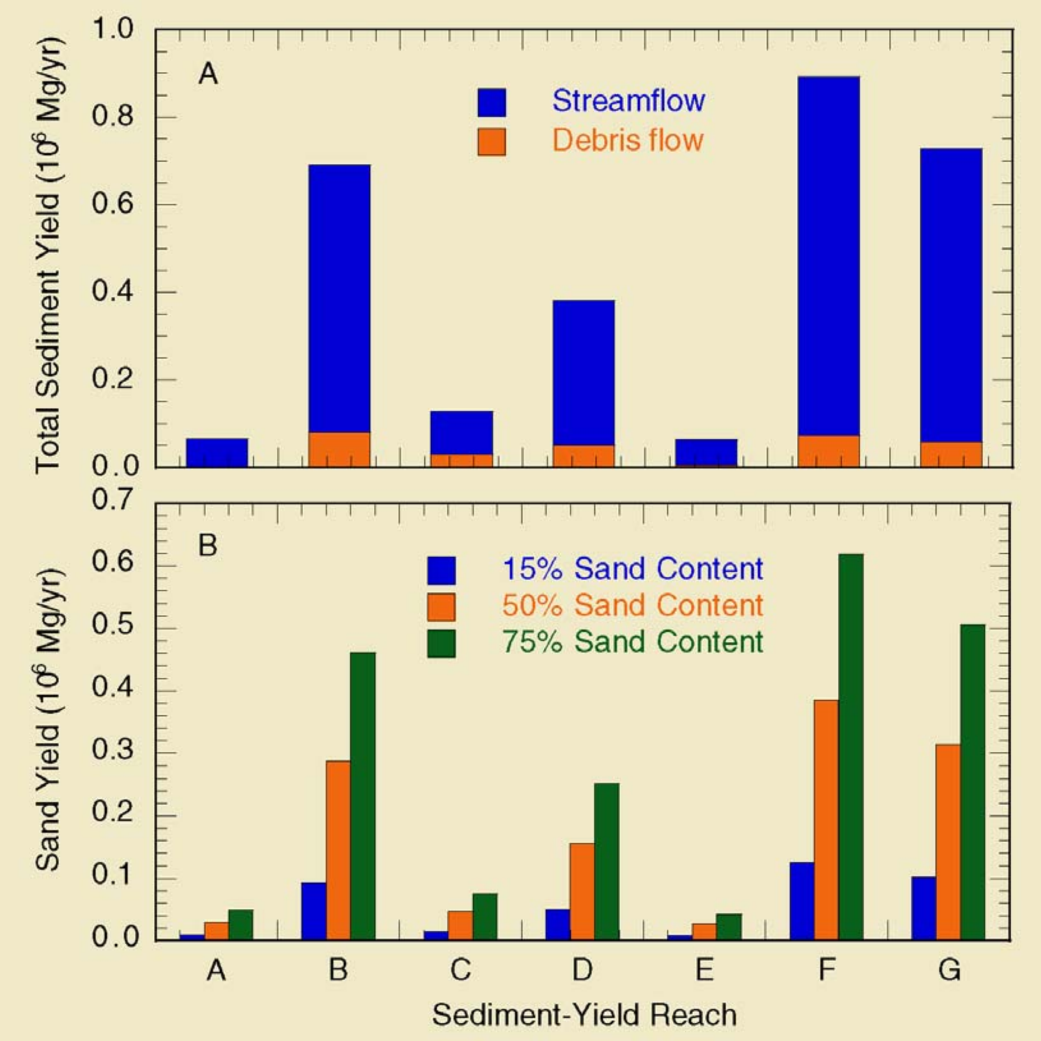
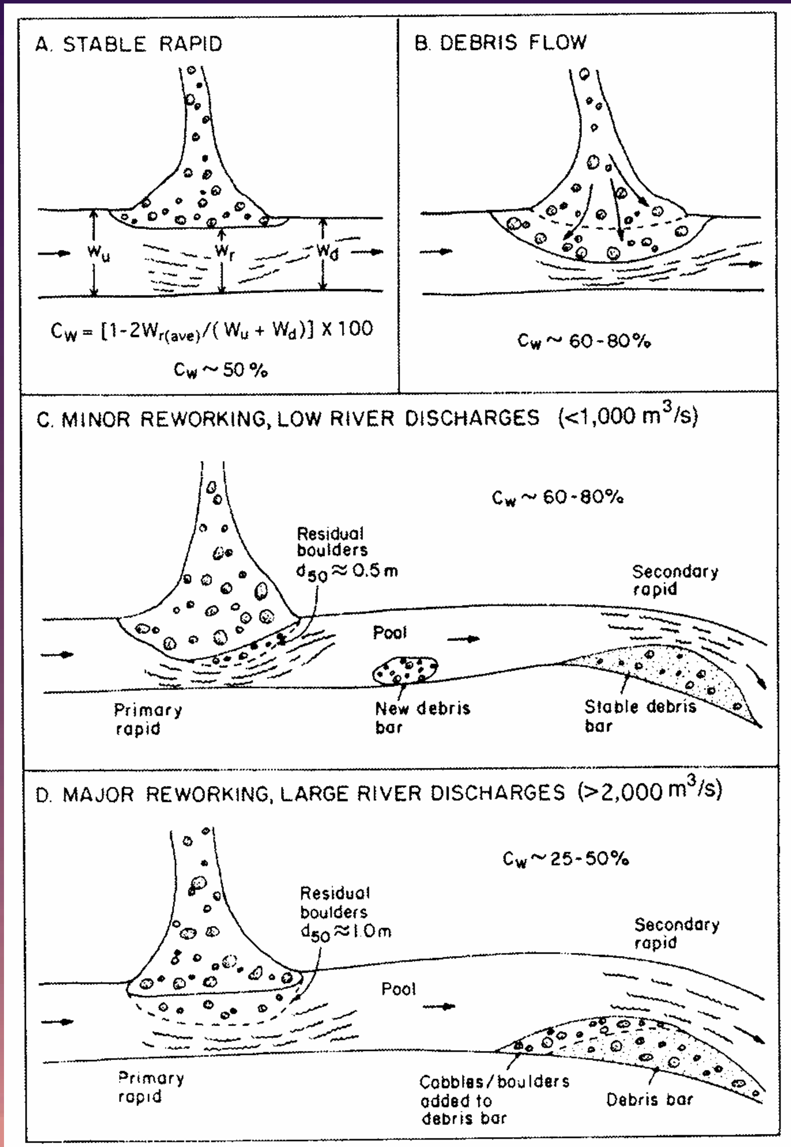
Sediment Yield of Grand Canyon Tributaries

Seven geomorphic reaches





Reach B: 25% of Paria inputs

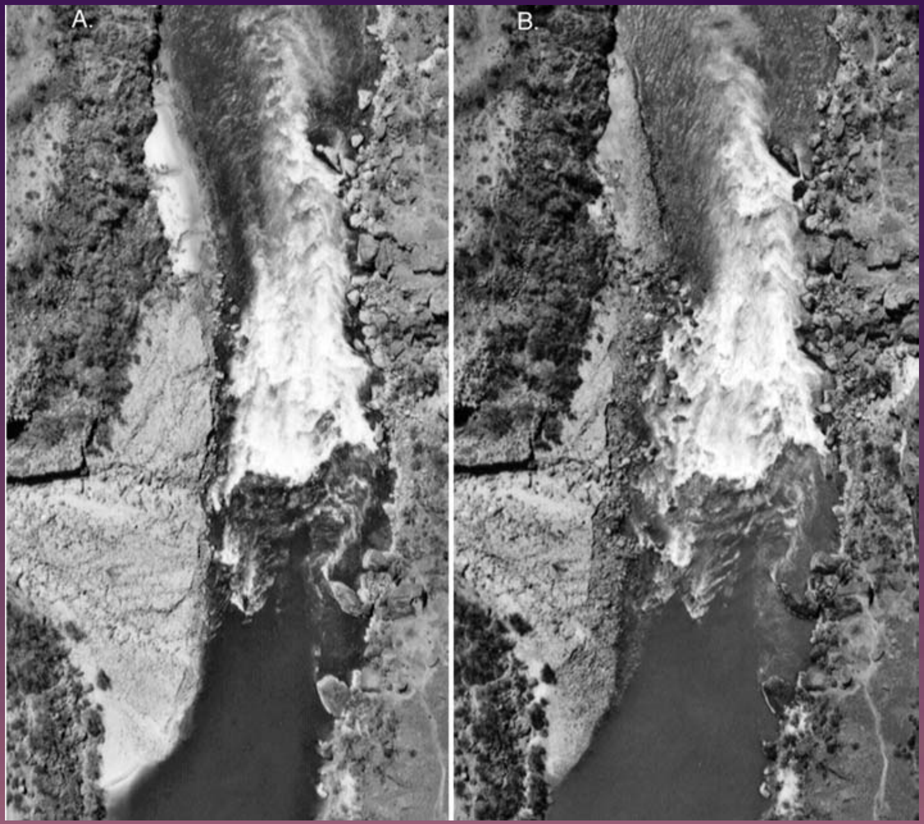


River Reworking

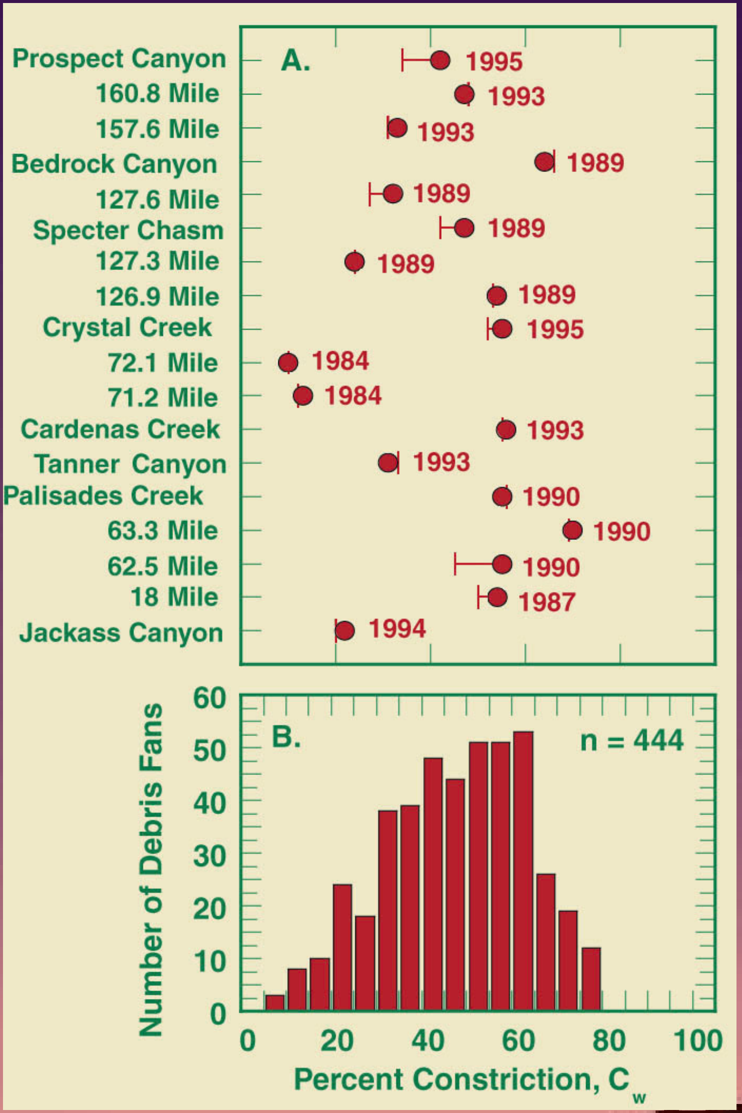
- Glen Canyon Dam completed in 1963
- Pre-dam floods (to 30,000 ft^3/s) removed all particles <3-6 ft (b-axis diameter)
- Post-dam floods (< 96,000 ft^3/s) move smaller particles up to 4.5 ft in diameter
- Particles now end up in the pool instead of the secondary rapid

Ref: Webb et al., 2000, USGS WRIR 00-4015

Reworking of Aggraded Debris Fans (the 1996 Flood)



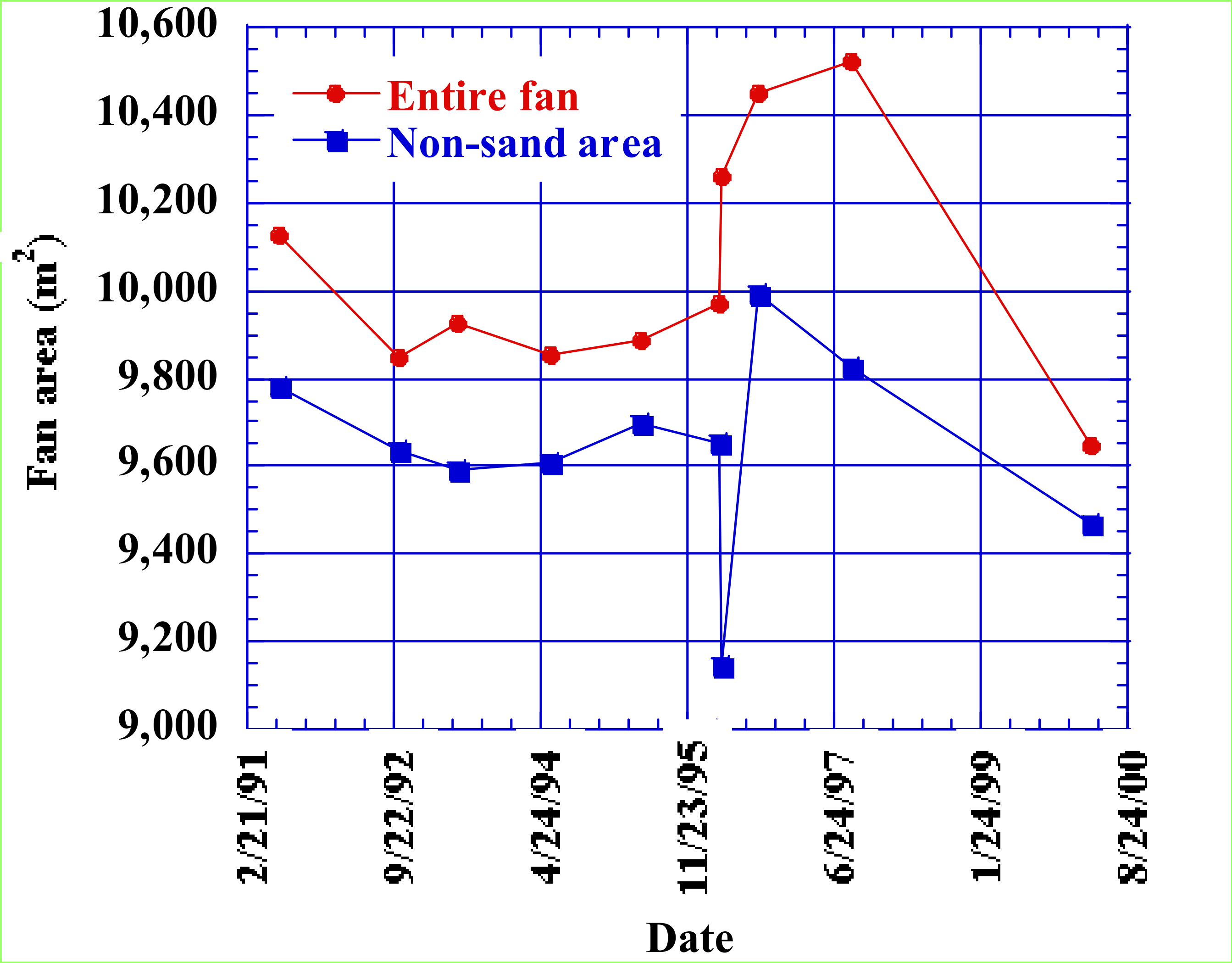
Lava Falls Rapid. A. March 25, 1996. B. April 6, 1996. The rapid widened by about 60 ft by reworking of 1995 debris-flow deposits.



Ref: Webb et al., 1999; Pizzuto et al., 1999

Reworking of Debris Fan at Granite Rapid

Photogrammetric analysis using ERDAS



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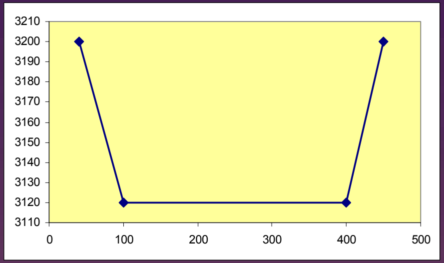
Future Work: 1-D Hydraulic Modeling

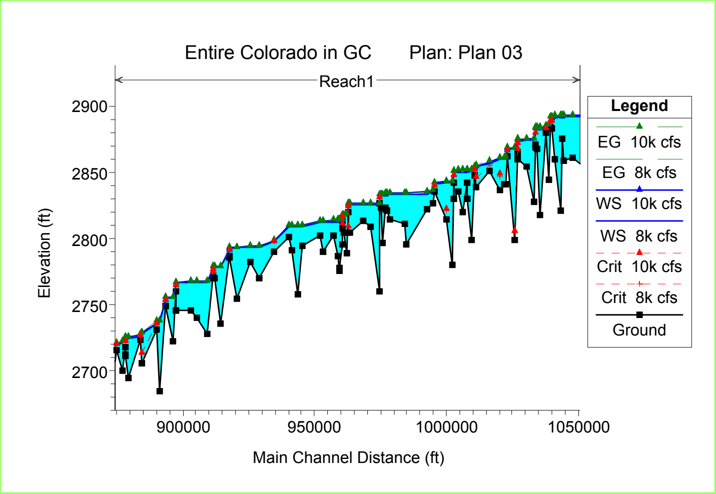
Randle and Pemberton (1987) STARS Model



- Based on 1923 and some 1984 data
- Limited to 30,000 ft^3/s peak discharge
- Most cross sections were idealized as trapezoids

Converted into HEC-RAS working model (2002)

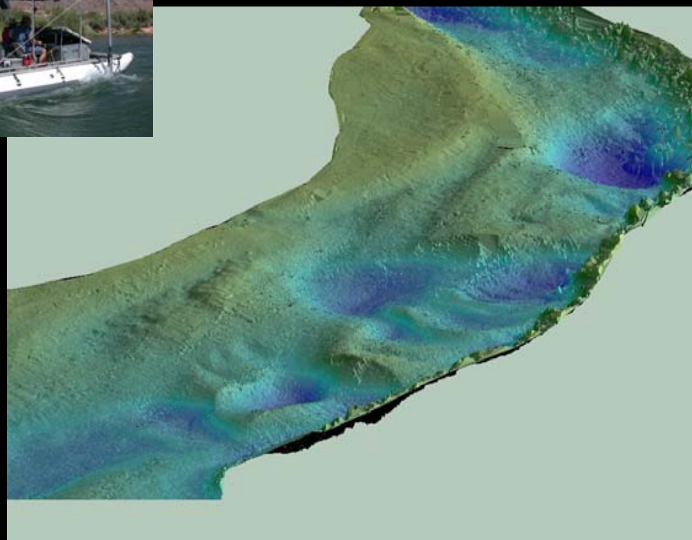
- Entire river length modeled
- Uses STARS cross sections (still based on 1923/1984 data)
- Ultimate goal is modeling of gravel and coarse particle transport for conceptual modeling



Improved Hydraulic Model using GCMRC Data

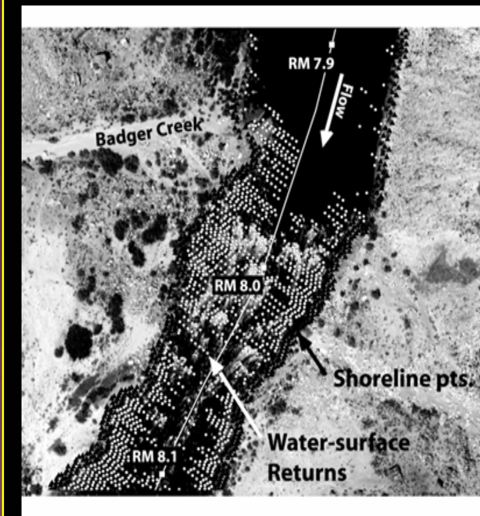
2002 Bathymetry

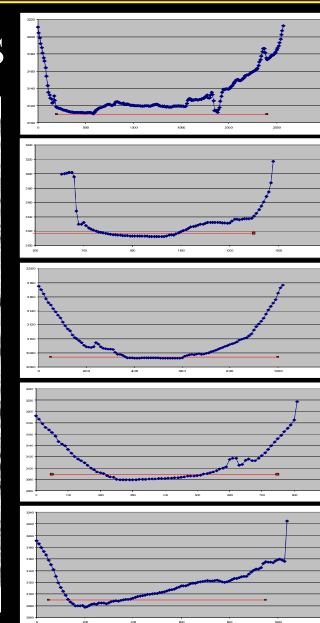
Mark Gonzales, GCMRC Survey



2002 LIDAR Topography

Mike Breedlove, GCMRC GIS





State-of-the-Art 1-D Hydraulics

GSTARS	HEC-RAS
Gravel transport	Inundation to PMF level
Fish spawning	Debris fan reworking
Sand storage	Combine w/ DF model

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Integrated Science

- 1-D and 2-D modeling in Glen and Marble Canyon in support of management of salmonids and suitability of fish habitat.
- Use results to drive conceptual model by Ecometric Research (Josh Korman).

-4.0 Bar

Nankoweap

Conclusions

- As Alan Howard and Robert Dolan predicted, the longitudinal profile through Grand Canyon is becoming an enhanced pool-drop profile as a result of operations of Glen Canyon Dam. This has "good" aspects (traps more sand for beaches, more challenging rapids) and "bad" aspects (more habitat for non-native fish).
- Modeling of sediment transport by episodic events such as debris flows is possible with sustained research effort.
- Reworking of aggraded debris fans is possible with higher than powerplant releases from Glen Canyon Dam (such as the 1996 flood). More frequent floods would move both gravel and boulders.
- We don't know why, but native fish are related to debris-flow frequency. More research by fisheries scientists is needed here.

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